Final Technical Report for the Project:
Wave Groups in Shallow Water, N00014-90-J-1021

The immediate scientific objective of this project was to understand the underlying dynamics and statistics of groups of ocean waves to predict their behavior throughout the shoaling region seawards of the zone of wave breaking.

Wave group prediction models based on linear theory were developed and implemented and compared to a range of observations, including sea-surface elevation measured in 19 m water depth near the North Carolina coast (SAMSON and Delilah field experiments, Aug 1990 - May 1991), 9 m water depth near the Southern California coast, and across a transect extending from the shoreline to 8 m depth near North Carolina (Duck94 experiment, summer-fall 1994). Comparisons of these data with models indicate for a wide range of ocean conditions (seaward of the shoaling region (approximately 10 m water depth)) wave group statistics are consistent with linear theory. The comparisons resulted in a PhD dissertation for Dr. Z. Liu.

Linear theory does not predict accurately observations of group statistics in shallow depths (eg, less than 10 m) where nonlinear interactions become important to the evolution of the wave field. Recent PhD graduate Barry Vanhoff developed a technique to numerically simulate a wave field with a specified power spectrum and bispectrum, thus allowing wave fields with quadratic nonlinearities to be simulated. Comparisons between observed and simulated group statistics demonstrate the technique is accurate, even for nearly-breaking waves.

One of the primary results of this study is that wave group statistics observed in the ocean at depths greater than 10 m for a large range of wave conditions are consistent with linear theory. Wave group prediction models that do not include the effect of correlations between waves separated by several intervening waves underpredict the number of sequential large waves. On the other hand, a model that includes correlations of waves separated by as many as six intervening waves predicts accurately the observed wave group statistics. Another result is that although computationally convenient, wave group prediction models based on power spectral shape alone are not as accurate as models based on direct simulations of the wave field. In shallower water where nonlinearities in the wave field can be important, linear theory based models underpredict the lengths of groups of large waves, but nonlinear simulations that use information from the power spectrum and bispectrum of the time series of sea-surface elevation are more accurate. The simulations suggest nonlinearities result in longer groups of high waves than occur in a Gaussian (eg, linear) sea.

ONR-Sponsored Publications

P = published
IP = in press
PS = paper submitted
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R = technical report
BC = book chapter

P- Elgar, Steve, M.H. Freilich, and R.T. Guza, 1990, "Model-data comparisons of moments of nonbreaking shoaling surface gravity waves," J. Geophysical Research, 95, pp. 16055-16063.

P- Chandran, V. and Steve Elgar, 1990, "Bispectral analysis of 2-D random processes," IEEE Acoustics, Speech, and Signal Processing, 38, pp. 2181-2186.

P- Pezeshki, C., Steve Elgar, and R.C. Krishna, 1991, "An examination of multi-frequency excitation of the buckled beam," J. Sound and Vibration 148, pp. 1-9.

P- Pezeshki, C., W. H. Miles, and Steve Elgar, 1991, "Signal Processing for nonlinear structural dynamical systems," ASME Applied Mechanics Reviews, 44, pp. S214-S218.

P- Chandran, V. and Steve Elgar, 1991, "Mean and variance of estimates of the bispectrum of a harmonic random process: an analysis including effects of spectral leakage," IEEE Signal Processing, 39, pp. 2640-2651.

P- Hagelberg, Teresa, Nick Pisias, and Steve Elgar, 1991, Linear and nonlinear coupling between orbital forcing and the marine $\delta^{18}O$ record during the late Neogene, Paleoceanography, 6, pp. 729-746.

P- Elgar, Steve, R. T. Guza, M. H. Freilich, and M. Briggs, 1992, " Laboratory simulations of directionally spread shoaling waves," ASCE Journal of Waterway, Port, Coastal, and Ocean Engineering, 118, pp. 87-103.

P- Wallerstein, G. and Steve Elgar, 1992, "Shockwaves in stellar atmospheres and breaking waves on an ocean beach," Science, 256, pp. 1531-1536.

P- Elgar, Steve, R.T. Guza and M.H. Freilich, 1992, "Dispersion, nonlinearity, and viscosity in shallow-water waves: Model results and laboratory comparisons," ASCE

Journal of Waterway, Port, Coastal, and Ocean Engineering 119, pp. 351-366.

P- Pezeshki, C., Steve Elgar, R.C. Krishna, and T.D. Burton, 1992 "Auto- and cross-bispectral analysis of a system of two coupled oscillators with quadratic nonlinearities possessing chaotic motion." Journal of Applied Mechanics 59, 657-663

P- Miles, W.H., C. Pezeshki, and Steve Elgar, 1992 "Bispectral analysis of a fluid elastic system; the cantilevered pipe, J. of Fluids and Structures 6, 633-640.

P- Elgar, Steve, T. H. C. Herbers, M. Okihiro, J. Oltman-Shay, and R.T. Guza, 1992 "Observations of infragravity waves," J. Geophysical Research, 97, 15573-15577.

P- Chandran, V., and Steve Elgar, 1993 " Pattern recognition using invariants defined from higher-order spectra: one-dimensional inputs," IEEE Acoustics, Speech, and Signal Processing, 41, pp. 205-212.

P- Liu, Z., Steve Elgar, and R.T. Guza, 1993 "Groups of ocean waves: comparisons between linear theory, approximations to linear theory, and observations," ASCE Journal of Waterway, Port, Coastal, and Ocean Engineering, 119, 144-159.

P- Elgar, Steve and M.P. Kennedy, 1993 "Bispectral analysis of Chua's circuit," J Circuits, Systems, and Computers, 3, 33-48. (reprinted in "Chua's Circuit: A paradigm for Chaos," Ed R. Madan, Series on Nonlinear Science, Series B, Vol 1, 892-907, World Scientific, Singapore, 1993)

P- Chandran, V., Steve Elgar, and C. Pezeshki, 1993 "Bispectral and trispectral characterization of transition to chaos in the Duffing oscillator," International Journal of Bifurcation and Chaos 3, 551-557.

P- Elgar, Steve and Vinod Chandran, 1993 "Higher-order spectral analysis to detect nonlinear interactions in measured time series and an application to Chua's circuit," International Journal of Bifurcations and Chaos, 3, 19-34.

P- Elgar, Steve, R.T. Guza, and M.H. Freilich, 1993 "Observations of Nonlinear Interactions in Directionally Spread Shoaling Surface Gravity Waves," J. Geophysical Research 98,20299-20305.

P- Elgar, Steve and Vinod Chandran, 1993 "Higher-order spectral analysis of Chua's circuit," IEEE Transactions on Circuits and Systems 40, 689-692.

P- Elgar, Steve, and James Kadtke, 1993 "Paleoclimatic attractors: New data, further analysis," International Journal of Bifurcations and Chaos 3, 1587-1590.

P- Chandran, V. and Steve Elgar, 1994, "A general procedure for the derivation of

principal domains of higher-order spectra," IEEE Signal Processing 42, 229-233.

P- Chandran, V., Steve Elgar, and B. Vanhoff 1994 "Statistics of tricoherence" IEEE Signal Processing 42, 3430-3440.

P- Herbers, T.H.C., Steve Elgar, and R.T. Guza, 1994 "Infragravity-frequency (0.005-0.05 Hz) motions on the shelf, Part I: Local nonlinear forcing by surface waves," J. Physical Oceanography 24, 917-927.

P- Herbers, T.H.C., Steve Elgar, R.T. Guza, and W.C. O'Reilly, 1995 "Infragravity-frequency (0.005-0.05 Hz) motions on the shelf, Part II: Free Waves," J. Physical Oceanography 25, 1063-1079.

P- Elgar, Steve, T.H.C. Herbers, V. Chandran, and R.T. Guza, 1995 "Higher-order spectral analaysis of nonlinear ocean surface gravity waves," Journal of Geophysical Research 100, 4977-4983.

P- Herbers, T.H.C., Steve Elgar, and R.T. Guza, 1995 "Generation and propagation of infragravity waves, J. Geophysical Research 100, 24,863–24,872.

IP- Chandran, V. B.Carswell, B. Boashash, and Steve Elgar, "Pattern recognition using invariants defined from higher-order spectra – two-dimensional inputs," IEEE Transactions on Image Processing, in press.

IP- Vanhoff, B., Steve Elgar, and R.T. Guza, "Numerically simulating nonGaussian sea surfaces," ASCE J. Waterway, Port, Coastal, and Ocean Engineering, in press.

PS- Vanhoff, B and Steve Elgar "Simulating quadratically nonlinear random processes," IEEE Transactions on Signal Processing, sub judice.

C-Elgar, Steve, M. H. Freilich, R.T. Guza, 1990, "Model predictions of non breaking shoaling waves," Proceedings of the 22nd International Conference on Coastal Engineering, Delft, Netherlands, ASCE.

C-Chandran, Vinod and Steve Elgar, "Shape discrimination using invariants defined from higher order spectra," Proc. of IEEE Int'l. Conf. on ASSP (ICASSP'91), vol. 5, pp. 3105-3109, May 1991.

C-Herbers, T.H.C., Steve Elgar, R.T. Guza, and W. O'Reilly, 1992, "Infragravity-frequency (0.005-0.05 Hz) motions on the shelf," Proceedings of the 23nd International Conference on Coastal Engineering, Venice, Italy, ASCE.

BC-Elgar, Steve, 1990, "Bispectral analysis of systems possessing chaotic motion," In *Nonlinear Dynamics of Ocean Waves*, Ed. Brandt, Ramberg, Shlesinger, World

Scientific, Singapore, pp. 111-127, 1992.

R-Holman, R.A., A. J. Bowen, R.A. Dalrymple, R. Dean, S. Elgar, R. Flick, M. Freilich, R. T. Guza, D. Hanes, J. Kirby, O. Madsen, R. Sternberg, and I. Svendsen, Report for the Nearshore Processes Workshop, St. Petersburg, FL., Report OSU-CO-90-6, Oregon State University, 42 pp., May 1989.

IC- Elgar, Steve, 1987, "Bispectra of shoaling waves," Proceedings of the Symposium of Nonlinear Interactions in Fluids," ASME, Boston, MA. (INVITED)

Statistics

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One of the primary results of this study is that wave group statistics observed in the ocean at depths greater than 10 m for a large range of wave conditions are consistent with linear theory. Wave group prediction models that do not include the effect of correlations between waves separated by several intervening waves underpredict the number of sequential large waves. On the other hand, a model that includes correlations of waves separated by as many as six intervening waves predicts accurately the observed wave group statistics. Another result is that although computationally convenient, wave group prediction models based on power spectral shape alone are not as accurate as models based on direct simulations of the wave field. In shallower water where nonlinearities in the wave field can be important, linear theory based models underpredict the lengths of groups of large waves, but nonlinear simulations that use information from the power spectrum and bispectrum of the time series of sea-surface elevation are more accurate. The simulations suggest nonlinearities result in longer groups of high waves than occur in a Gaussian (eg, linear) sea.

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